Section 2.0
Technology Description

2.1 Description

2.1.1 Waste and Media Application

Phytoextraction is an *in situ* remediation method which uses plants to remove ionic metals (e.g., lead) from contaminated soils. Ionic metals are commonly produced when metal-bearing propellants, ammunitions, and powders are burned on the soil surface or particulate lead dissolves. Ionic lead contamination may also occur when leaded chemicals or fuels are spilled. Particulate elemental lead, bullet fragments for example, cannot be treated by this process. Phytoextraction methods may practically be used to remediate soils contaminated with lead in the 100 to 2,000 ppm range. For the technology to work, at least 50% of the total soil lead should be in a form amenable to extraction by plants. Expectations for reduction in soil lead concentrations are in the range of 100 to 200 mg lead/kg soil per year. Treatment at higher soil lead concentrations is technically feasible; however, the time required to achieve complete remediation will be excessive and unrealistic.

2.1.2 Description of Technology

In phytoextraction, heavy metals are taken up in plant tissues in sufficient concentrations to cause plant death. After the plants die, the plant shoots are harvested and can either be processed for metals recovery or disposed of as a hazardous waste. In contrast to some other remediation methods, phytoextraction techniques allow for the extraction and recovery of metals *in situ*; mechanical removal of the soil should not be necessary.

The extraction of ionic lead by plants is the primary focus of this technology. However, lead is not easily taken up by plants and removed from soil. Lead is considered the least soluble, the least mobile, and the least plant-available of the heavy metals in soils. Ionic lead (Pb^{2+}) is usually present in soil in various insoluble solid phases (i.e., lead carbonate - $Pb_3(CO_3)_2(OH)_2$, lead cerrusite - $PbCO_3$, lead phosphates, etc.) which do not readily release lead into the soil solution; thus, plant availability of lead is generally low. Lead also tends to accumulate within the root structures of most plants rather than moving to the aerial shoots. Before being taken up by a plant, lead in solid phases must be dissolved and released into the soil solution as ionic lead. The lead then is absorbed into the plant roots and translocated from the roots to the plant shoots.

In phytoextraction, plant uptake of lead may be increased by adding soil amendments to increase lead solubility. Solubilization makes lead more available for plant uptake. The soluble forms of lead easily move into the plant roots and are translocated to and accumulate in the aboveground shoots of certain plant species at much higher concentrations than would otherwise occur. The use of these amendments with selected plant species allows lead accumulation of up to 2% in the aboveground portion of the plant.

Soil amendments currently used for phytoextraction are soil acidifiers and chelates. Soil acidifiers, such as acetic acid, temporarily increase soil acidity which solubilizes lead out of soil solid phases and into the solution phase of the soil (the soil solution). Chelates, such as EDTA, enhance solid phase solubilization by chelating the lead that is in solution and shifting the equilibrium toward further dissolution (i.e., lead ions combine with the chelating agent, thereby, removing ionic lead from the liquid phase and promoting additional release of the solid phase lead into the liquid phase). Chelation may be viewed as the multiple bonding of a metal to coordinating groups (or ligands) of an organic compound to form a stable charge transfer structure which protects the metal ion from reacting with the soil to form insoluble compounds.

There are several components of a phytoextraction scheme. The "processing unit" of a lead phytoextraction system consists of a plowed field of the contaminated soil, a crop, an irrigation system, a fence, the necessary farm equipment, decontamination equipment, and a decontamination area. The decontamination area is used for decontamination of personnel and farm equipment leaving the contaminated area. The addition of soil amendments greatly enhances lead uptake by the plants; however, plant species vary considerably in ability to take up lead, even when it is in a soluble form. Plant species that have suitable characteristics for lead remediation are corn, alfalfa, Indian mustard, and white mustard.

To "operate" the field, a crop, which is chosen for good growth in the climate of the area, is planted and grown to full vegetative biomass maturity (i.e., to a stage just before fruit or grain production) using common farm practices. After the plants have matured, the amendments are added to the soil to solubilize lead into a plant-available form. Within a few days, the plants begin to senesce (die) due to uptake of large amounts of lead and chelate. After plant death, the shoots are harvested, either by use of common farming techniques or by hand. The harvested crop is then either disposed of as a hazardous waste or processed (smelted) for metals recovery. The number of extraction crops that can be grown to full vegetative biomass depends on the type of plant and local climate and may range from one to four crops per year. When possible, a cover crop may be grown in the winter season to control wind and water erosion. The cover crop is tilled back into the soil prior to planting the spring crop. Examples of common cover crops are wheat, barley, and annual and perennial ryegrass.

2.2 Strengths, Advantages, and Weaknesses

Several strengths and advantages have been attributed to phytoremediation. However, this demonstration showed that in this particular case, the weaknesses outweighed the advantages. The feasibility of implementing a phytoextraction program at a particular site is influenced by the following factors:

- The lead content of the soil
- The underlying geology
- The potential for phosphorus deficiencies in the soil
- Local weather conditions
- Plant selection
- Chelator cost
- Size of area to remediate
- Time limitations for remediation
- Regulatory requirements within a state

Sites with lead concentrations within 200 - 300 mg ionic lead/kg soil of the clean-up level are the most suitable for phytoextraction, since this type of site could be remediated within 5 years. However, the expected reduction in soil lead ranges from 50 - 100 mg lead/kg soil per year, so the time required to successfully conclude a remediation program may become unrealistic for higher concentrations.

The underlying soil geology may also be a concern. Soil amendments increase lead solubility and it is possible for lead to move out of the plant root zone into lower soil layers, adjoining areas, or groundwater. Therefore, careful attention must be paid to the nature of the underlying geology (soil texture, clay content, hydraulic conductivity, soil moisture, depth of water table, etc.), as well as the levels of soil amendment application.

Phosphorus (P)-deficient soils may complicate phytoextraction schemes. Lead-contaminated soils tend to be deficient in plant-available phosphorus because some of the applied phosphorus may precipitate with lead as insoluble lead-phosphate complexes. The symptoms of phosphorus deficiency include decreased plant growth and decreased biomass production. Phosphorus deficiency lowers remediation effectiveness by reducing total lead uptake.[Ref. 3] This can be remedied by supplying additional phosphorus to the plant, either by foliar application (i.e., spraying a water-soluble phosphate fertilizer solution directly on the plant) or by band application of phosphorus at planting (i.e., applying bands of phosphate fertilizer below the soil surface and to the side of the plant or seed row). However, this can easily be done only with crops that are planted in rows, such as corn. This may not be practical for crops that are broadcast-seeded, such as mustard.

Local weather conditions affect the length of the growing seasons, the type of crop to be grown, and crop sequence. In turn, the types of plants to be grown at a site are subject to evaluation for a number of considerations including: the length of the growing season, the availability of rainfall and rainfall accumulations, adaptability to local conditions, soil fertility, and ability to take up lead. Corn (*Zea mays*) appears to be the most suitable warm season crop, while white mustard (*Sinapis alba*), Indian mustard (*Brassica juncea* L.), and alfalfa (*Medicago sativa* L.) appear to be suitable cool season crops.

Chelate costs are a major part of the expenses for a phytoextraction project and fluctuations in prices may significantly impact projected budgets. If feasible, long-term contracts with the vendor to supply the required amount of chelate over the life of the project at a pre-set cost would be very desirable.

The size of the area to be remediated directly affects both the level and type of labor and equipment required, which in turn affect cost. A practical area size limit for completion using manual practices (i.e., soil core sampling, hand tilling, planting, and harvesting) would be half an acre. Larger areas will require the use of mechanized equipment. Manual labor is initially cheaper, but there will be a point where this cost savings will quickly be offset by the time and effort required to accomplish each task. At that point, mechanized equipment becomes more practical.

The time required to phytoextract an area is a function of the potentially extractable and plant-available lead concentration in the soil and the cleanup level (residential or industrial standard) to be achieved. In most cases, phytoextraction is slower than other methods. The ultimate use of the area dictates the maximum time that can be allotted for remediation. For example, simple economics dictate that an area designated for general construction will require a more expedient method than phytoremediation for cleanup. However, if there are no immediate plans for use of the area, and all that is required is that the area be cleaned up, then phytoextraction will be entirely suitable.

Additional aspects of phytoextraction relative to other remediation technologies include:

- Low remediation costs, ranging from $25 to $127 per cubic yard.[Refs.17,18]
- Heavy metals removal by plant harvesting minimizes site disturbance and limits the dispersal of contaminants.
- Heavy metals recycling is possible via the processing (smelting) of the harvested plant tissues.
- If the heavy metals are recycled, the cost and long-term liability associated with maintaining a landfilled hazardous waste is substantially reduced or eliminated.
- Operating space requirements are limited to the field being treated.
- The technology is relatively simple and easy to implement.

Relative to other technologies, phytoremediation also has a number of weaknesses:

- Can require several years for remediation.
- Only applies to limited situations (lead concentrations, site conditions, soil type).
- Will be prohibitively expensive for higher soil lead concentrations.
- Technology is greatly impacted by weather and other environmental factors.
- May require liners to prevent lead leveling, which will increase costs.
- EDTA is an effective chelate for solubilizing lead, but carry-over EDTA may become toxic to plants.

2.3 Factors Influencing Cost and Performance

Factors which affect the cost and performance of phytoextraction technology include:

- Soil (Matrix) Properties
  - Soil type
  - Clay content and/or particle size distribution
  - Hydraulic conductivity
  - Moisture content
  - Porosity
  - pH
  - Contaminant depth

- Properties of Organics in Soil
  - Total organic carbon

- Non-Matrix (non-soil) Characteristics
  - Contaminants
  - Ambient temperatures
  - Geology and hydrogeology
  - Cleanup levels
  - Weather conditions (rainfall, drought)
  - Growing season
  - Chemical costs

The potential effects of each of these factors on cost or performance are listed in Table 2-1 and procedures for measuring these parameters are listed in Table 2-2.

Other factors which can be relevant to the performance of the technology are outlined in Table 2-3 in accordance with the guidelines given in "Guide to Documenting and Managing Cost and Performance Information for Remediation Projects:"[Ref. 19]

- The applicability of the technology to a specific situation
- Competing technologies
- The maturity of the technology

The implication of these factors are outlined in Table 2-3.

Table 2-1

Matrix Characteristics and Operating Parameters that Affect Phytoremediation Technology Treatment Cost or Performance

Parameter	Potential Effects on Cost or Performance
Matrix Characteristics	
Soil Properties	
Soil Type	1. Sand and sandy loam soil types are conducive to leaching of nutrients; consequently, natural fertility usually is low and nutrient deficiencies may develop in plants. Applied chelate and inorganic contaminants solubilized by the chelate may be subject to downward movement, which may move contaminants of interest beyond the root interception zone of remediation crop, and uptake by crop may be reduced. 2. Mineralogy of soil--an enriched iron oxide content will promote strong adsorption of chelate, which may reduce chelate effectiveness or may result in carryover to successive crops.
Clay Content and/or Particle Size Distribution	1. Presence of clay lenses or a fine clay/sand hardpan layer increases difficulty and labor requirements of sampling. 2. Also results in reduced and non-uniform infiltration (areas over-saturated or under-saturated) of added soil amendments (chelate and acidifier) which may result in loss by runoff and reduced amount in root zone (treatment effectiveness compromised).
Hydraulic Conductivity	1. Variable in sandy loam from slow to fast. This results in variable infiltration rates and non-uniform amendment application and placement within crop; potential for runoff increased. 2. Fast in sand. May result in too rapid downward movement of amendments and reduced contact time with roots--reduced treatment effectiveness. 3. Slow in clay. May result in restricted downward movement of amendments and prolonged contact time with roots--reduced treatment effectiveness. May result in runoff of soil amendments.
Moisture Content	Soil moisture should be regulated by selective irrigation so that the required amount of soil amendment may be applied in a volume which does not exceed field capacity in the top 2 feet of soil (rooting zone).
Porosity	Directly affects the water-holding capacity and field capacity of soils.
pH	1. Must be within the tolerance range of crop to be grown for efficient nutrient utilization and maximum yield. 2. pH is reduced to 5.5 to facilitate solubilization of inorganic contaminants into plant-available form and to increase efficiency of chelate.
Contaminant Depth	Contamination in soil must be restricted to a depth accessible to plant roots (usually top 2 to 3 feet).
Properties of Organics in Soil	
Total Organic Carbon	This influences important soil chemical and physical properties, i.e., fertility, exchange capacity, and moisture-holding capacity. This may also affect reactions of inorganic contaminants (metals, oxyanions) both before and after solubilization by amendments.

Table 2-1 (Continued)

Matrix Characteristics and Operating Parameters that Affect Phytoremediation Technology Treatment Cost or Performance

Parameter	Potential Effects on Cost or Performance
Matrix Characteristics	
Non-Matrix Characteristics	
Contaminants	The primary contaminant of interest should have the greatest interaction with the soil amendments (acidifier and chelate) and the selected amendments should be tailored to the primary contaminant. Other Contaminants of Concern (COCs) should be identified and quantified and a determination made of potential adverse effects on crop growth. Crops with low tolerance to any contaminants should not be grown.
Ambient Temperature	Ambient temperature affects metabolic processes of plants. Lower temperatures may reduce rates of uptake and assimilation.
Geology and Hydrogeology	Heterogeneous material, i.e., sandy soil with gravel and cobbles, will increase sampling difficulty and will promote variable hydraulic rates. May limit usefulness of suction lysimeters as monitoring tool for solubilized metals in soil solution. A shallow or perched water table may be subject to contamination by amendments and solubilized COCs and may reduce percolation rates. Heavy clay soils may inhibit infiltration. Direction of flow should be considered to determine suitability of site for amendment application. Shallow hard pan restricts root growth and encourages shallow rooting.
Cleanup Levels	Technology may not be suitable for reducing all COCs to appropriate level or the desired level may not be achievable within an appropriate timeframe. There may be a wide disparity in cleanup levels among the COCs. A dual level (industrial and residential) may exist for some contaminants.

Table 2-2

Measurement Procedures for Matrix Characteristics and Operating Parameters That Affect Phytoremediation Technology Treatment Cost or Performance

Parameter	Measurement Procedures
System Parameters	
Soil Classification	Official Soil Series Descriptions, USDA-NRCS Soil Survey Division, Iowa State University
pH	ASA Method 12-2.6
Temperature	Standard ambient temperature mercury thermometer
Porosity	ASA Method 8-2.3, *Water Retentivity.*
Biological Activity	
Nutrients/Soil Amendments	1. Organic Carbon measured by ASA Method 29-3.5.2; nitrogen as ammonia by ASTM D 1426-89, *Test Methods for Ammonia Nitrogen in Water*; nitrogen as nitrite-nitrate by ASTM D 3867-90, *Test Method for Nitrite-Nitrate in Water*; phosphorus by ASTM D 515-88, *Test Methods for Phosphorus in Water*; aluminum, calcium and magnesium by ASA 9-3.1; extractable iron by ASA Method 17-4.3. 2. EDTA in soil and plants by Method AP-0057 and Method AP-0047.
Plants Per Unit Area and Plant Type	1. Representative areas in remediation plots selected and measured, area calculated, and number of growing plants in area counted. Total plant population calculated by extrapolation to a per acre basis. 2. Amount of biomass produced determined by subsample weighing and extrapolation to total field area and by actual weight determination at disposal site, i.e., a smelter.

Table 2-3

Other Factors Affecting Project Demonstration Performance

Applicability of the Technology

- Phytoextraction is suitable for the range of lead concentrations (100 to 2,000 mg/kg) present in demonstration sites. Sites with higher lead concentrations may be remediated without interfering with plant growth. However, the expected lead reduction in soil ranges from 50 to 100 mg/kg per year and time constraints may limit use for higher concentrations.
- Technology usefulness may be limited by the sandy soils on demonstration sites which are conducive to downward movement of solubilized metals, as well as EDTA.
- Highly stratified soil with hardpan near surface may restrict root growth, encourage shallow rooting, and reduce infiltration while promoting runoff of added soil amendments.
- Stratified soils of varying texture within the soil profile restrict use of lysimeters for monitoring potential downward movement of chelate and contaminants.
- Presence of clay lenses may result in non-uniform infiltration of amendments across the continuum of the demonstration area.
- Presence of beryllium and thallium, even at very low soluble concentrations (2 ppm) in soil, may limit plant growth and sensitive accumulator crops may be severely damaged. These elements show indication of solubility into plant-available form by application of soil amendments or into a form which may migrate through soil, causing damage to roots. Therefore, phytoextraction may not be suitable for soils which contain these elements.
- The forms of soil lead govern the potential amount of lead that may be solubilized by a chelate, and thus the amount of lead available to plants.
- Application of the technology will be severely limited in areas having a shallow and/or fluctuating groundwater table that periodically intrudes into the amendment-treated rooting zone.

Competing Technologies

- Phytoextraction competes with conventional established technologies such as landfilling, soil washing (separation), *in situ* soil flushing, and containment.
- Commercial-for-profit vendors are actively promoting and using phytoextraction. However, methods are proprietary and operational success is not certain at present.

Maturity of the Technology

- Phytoextraction is an emerging technology and the methodologies and processes of applying the technology are still being defined through demonstrations. Several problematic areas, for example, chelate application methods, application rates, and chelate persistence in soil remain to be satisfactorily addressed and resolved.
- Current technology demonstrations and contaminants being addressed are: Arden Hills, Minnesota (lead); Bayonne, New Jersey (lead; Palmerton, Pennsylvania (zinc and cadmium); Liberty Park, New Jersey (chromium); Trenton, New Jersey (lead); Butte, Montana (cadmium, zinc, and radioactive cesium and strontium); and at the Superfund Innovative Technology Evaluation (SITE) Program site in Ohio (cadmium, lead, and hexavalent chromium).